

## Bremsstrahlung spectra of metallic targets produced by $^{32}\text{P}$ beta particles

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**Abstract** External bremsstrahlung (EB) spectra excited by  $^{32}\text{P}$  beta particles in thick targets of Al, Cu, Sn and Pb have been studied by using a high-efficiency scintillation detector. After making the necessary corrections, the experimental distributions were compared with the theoretical distributions obtained from the modified Elwert factor (relativistic) Bethe-Heitler ( $F_{\text{mod}}\text{BH}$ ) theory [N B Avdonina and R H Pratt, *J Phys B At Mol Opt Phys* **22** 1261 (1999)], Tseng and Pratt theory and Elwert corrected (non-relativistic) Bethe-Heitler (EBH) theory. The results of present measurements on low  $Z$ -elements show an agreement with all theories, within 8 to 10% throughout the studied energy region. For medium  $Z$ -elements, the experimental results are in agreement with the Tseng and Pratt and modified Elwert factor (relativistic) Bethe-Heitler theories. However, for high  $Z$ -elements, particularly at high-energy end, the experimental results show a better agreement with the modified Elwert factor (relativistic) Bethe-Heitler theory.

**Keywords** Bremsstrahlung spectra, beta particles, metallic targets

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### 1. Introduction

The external bremsstrahlung (EB) spectra generated by complete absorption of beta particles in thick metallic targets have been studied by various workers by using a high efficiency NaI(Tl) scintillation. Bremsstrahlung from nuclei is an important radiation process in plasma physics and astrophysics.  $^{32}\text{P}$  ( $\Delta J = 1$ , no) is an allowed beta emitter with an end point energy of 1.706 MeV. Liden and Starfelt [1], Prasad Babu *et al* [2], Ahmed *et al* [3] and Dhaliwal *et al* [4] have studied external bremsstrahlung (EB) from  $^{32}\text{P}$  beta particles in various metallic targets. The experimental spectra for medium and high  $Z$ -elements were found to agree with the Tseng and Pratt theory, while for low  $Z$ -elements EBH and Tseng and Pratt theories were equally suitable. However, a comparison of experimental EB spectra with the modified Elwert factor (relativistic) Bethe-Heitler ( $F_{\text{mod}}\text{BH}$ ) theory, given by Avdonina and Pratt [5], is not available in literature. In the present studies, the comparison of experimental EB spectral distributions of Al, Cu, Sn and Pb excited by  $^{32}\text{P}$  beta particles, have been made with the various theoretical distributions

obtained from Elwert corrected (non-relativistic) Bethe Heitler (EBH), Tseng and Pratt and  $F_{\text{mod}}\text{BH}$  theories. In order to exclude the uncertainty in the measurement of beta source strength, the theoretical and experimental results were compared in terms of number of photons of energy  $k$  per  $m_0c^2$  per unit photon yield versus photon energy ( $k$ ).

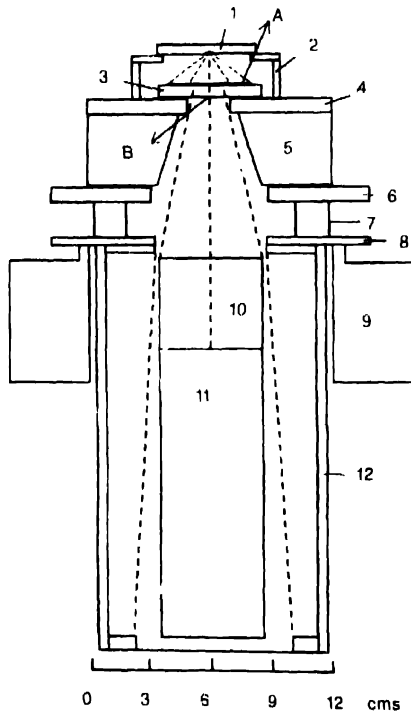
### 2. Theory

Sommerfeld developed a EB theory for non-relativistic electron while Bethe and Heitler [6] obtained an analytical expression for EB cross section [ $\sigma_{\text{BH}}(k)$ ] for the relativistic case by neglecting the Coulomb field effects of the nucleus by using the Born approximation. Koch and Motz [7] have reviewed the external bremsstrahlung studies in detail. Elwert [8] obtained a multiplicative Coulomb correction factor ( $F_{\text{Elwert}}$ ) for the Bethe-Heitler EB cross section,

$$F_{\text{Elwert}} = \frac{\beta_f (1 - \exp(-2\pi Z\alpha / \beta_i))}{\beta_i (1 - \exp(-2\pi Z\alpha / \beta_f))} \quad (1)$$

where  $\beta_i$  and  $\beta_f$  are the velocities of incoming and outgoing electrons. This factor was obtained from the comparison of non-relativistic Born approximation and the non-relativistic Sommerfeld calculations. Hence, this factor is applicable only to non-relativistic low energy electrons and fails to explain the results for high energy region of bremsstrahlung spectrum, where the outgoing electron is slow

More accurate theory for EB was developed by Tseng and Pratt [9] by using the (screened) self-consistent field wave functions for electron-nucleus bremsstrahlung. Later on, Seltzer and Berger [9] incorporated the electron-electron bremsstrahlung contributions to the electron-nucleus bremsstrahlung. Recently, Avdonina and Pratt [5] have shown that it is possible to substantially improve the analytical characterization of the coulombic bremsstrahlung cross section upto 2 MeV for elements of the periodic table. They have proposed a relativistic modification of the Elwert factor ( $F_{\text{mod}}$ ) by replacing  $\beta_{\text{eff}}$  in relation (1) with the momentum  $p_{\text{eff}} = [T_{\text{eff}}(2 + T_{\text{eff}})]^{1/2}$  obtained by using relativistic kinematics. Here,  $T_i$  and  $T_f$  are the initial and final energies of the electrons. In case of low energy electron bremsstrahlung  $\beta_{\text{eff}} = p_{\text{eff}}$ , the non-relativistic and relativistic Elwert factors are the same, hence this modification is applicable only in the higher energy region of bremsstrahlung spectrum.



**Figure 1.** Experimental setup (1) source holder, (2) perspex stand, (3) perspex beta stopper, (4) perspex sheet, (5) collimator, (6) ebonite plate, (7) lead annular ring, (8) copper plate, (9) lead castle, (10) NaI (Tl) crystal, (11) PM T shielded with mu - metal and (12) iron cylinder.

A simple analytical expression was obtained for EB cross section by using modified Elwert factor ( $F_{\text{mod}}$ ) and introduction of an empirical high order Born correction  $C(T_i, Z)$ ,

$$C(T_i, Z) = 1 + 0.25 (Z\alpha)^2 (2 - T_i). \quad (2)$$

Taking into account the correction (2) and the modification of the Elwert factor (1), the bremsstrahlung cross section is given by

$$\sigma_{\text{cor}}(k) = C(T_i, Z) F_{\text{mod}} \sigma_{\text{BH}}(k). \quad (3)$$

The various EB theories discussed above give the photon energy distributions for monoenergetic electron incident on very thin targets. However, Bethe and Heitler [6] gave an expression for EB spectral distribution where a target with  $N$  atoms per unit volume is sufficiently thick to absorb an electron of energy  $W_i$ . The total number of EB photons of energy  $k$  are given by

$$n(W_i', k) = N \int_{+k}^{W_i'} \frac{(d\sigma/dk)}{(dW_e/dx)} dW_e, \quad (4)$$

where  $(-dW_e/dx)$  is the total energy loss per unit path length of an electron in a target. In case of a beta emitter with the total end point energy of  $W_{\text{max}}$ , the bremsstrahlung spectrum is given by  $S(k)$  i.e. the number of photons of energy  $k$  per unit energy interval (in  $m_0 c^2$ ) per beta disintegration

$$S(k) = \int_{k+k}^{W_{\text{max}}} n(W_e', k) P(W_e') dW_e', \quad (5)$$

where  $P(W_e') dW_e'$  is the spectrum of the beta emitter under study [11].

In the present work for thick target, the theoretical EB spectral distributions for Al, Cu, Sn and Pb, excited by  $^{32}\text{P}$  beta particles, were obtained from EBH, Tseng and Pratt and  $F_{\text{mod}}$  BH theories. For Tseng and Pratt theory, the tabulated cross sections given by Pratt *et al* [12] were used. Finally, the results were converted into number of photons of energy  $k$  per  $m_0 c^2$  per unit photon yield and plotted against photon energy ( $k$ ) as shown in Figures 2(a-d).

### 3. Experimental details

The experimental setup shown in Figure 1 used to record the EB spectra of different metallic targets consisted of a well-shielded NaI(Tl) detector (4.5 cm diameter and 5.1 cm thickness) connected to a multichannel spectrometer. Most of the experimental details are similar to those described earlier by Dhaliwal *et al* [4]. A thin beta source of  $^{32}\text{P}$  was placed at distance of 10 cm from the face of the detector. A Perspex beta stopper technique was used to eliminate the contributions of the internal bremsstrahlung (IB), the EB generated in the source material, and room background

to get correct information regarding the intensity distributions of EB in a target material. Two sets of measurements were taken after calibrating the spectrometer. In the first measurement the target was placed on the perspex beta stopper on the collimator

of various corrections are explained elsewhere by Dhaliwal *et al* [4]. These corrections were necessary to transform the spectra recorded by the detector into one emitted by the target. The EB spectra were then reduced to the number of photons of energy

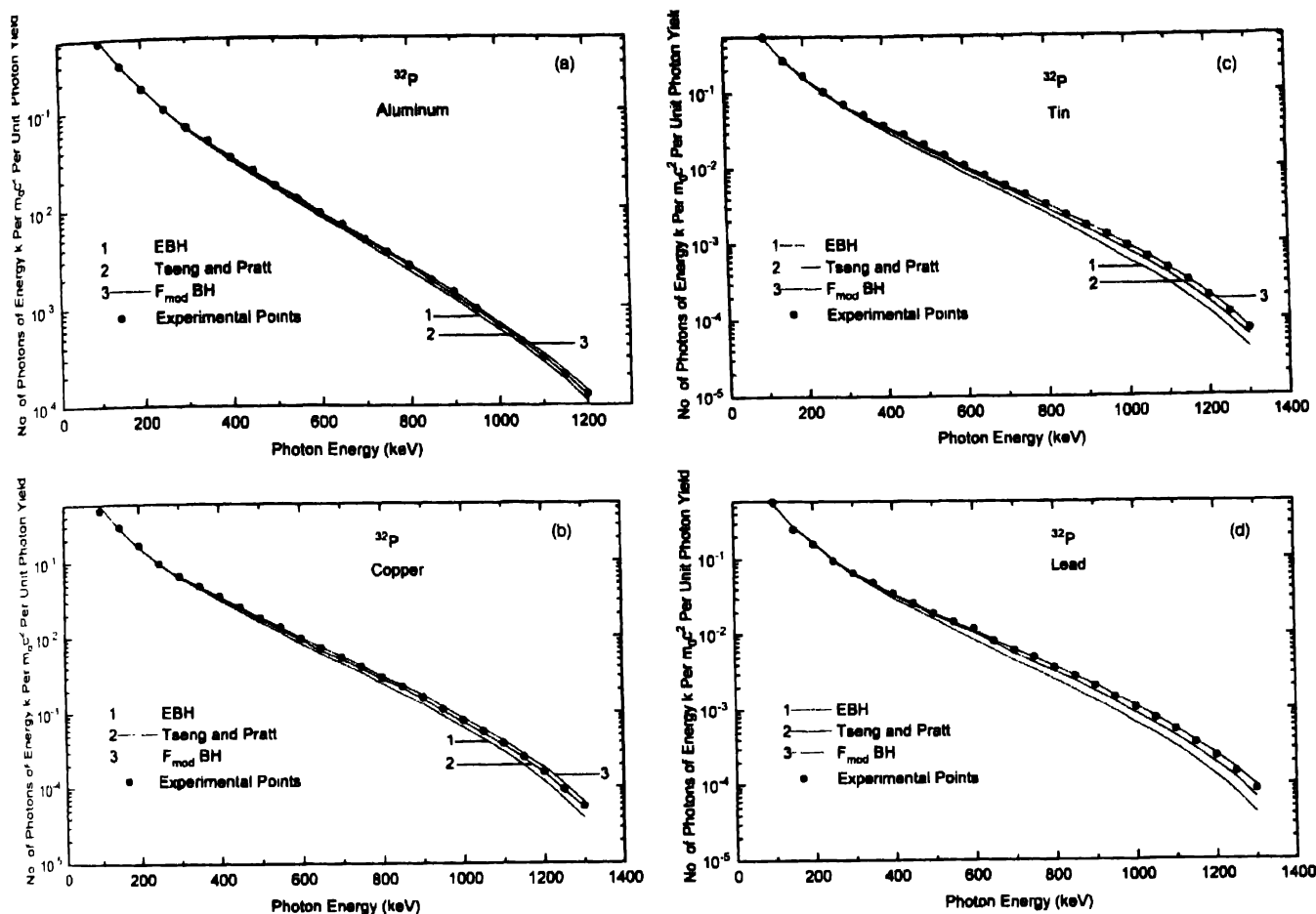


Figure 2 (a - d) Plots of number of photons of energy  $k$  per  $m_0c^2$  per unit photon yield versus photon energy (errors are lying within the experimental points and are quoted in the text).

Position A). This recorded the contributions of EB(target), IB, B(source) and room background. For the second measurement, the target was placed below beta stopper (Position B) so that the beta particles did not reach it. This measurement recorded the contributions of IB, EB (source) and room background. The difference of the above two measurements gave the EB intensity coming from the target. The measurements were conducted over long intervals of time to improve the statistics of the data to a value better than 3% at 1000 keV photon energy. The experimental EB spectral distributions were obtained by using thick targets of Al, Cu, Sn and Pb.

Various corrections, such as corrections due to energy resolution, iodine K X-ray escape, Compton continuum, detector efficiency and the corrections for absorption of bremsstrahlung in air, target material and the perspex beta stopper, were applied to the experimentally measured EB spectra. Details for evaluation

$k$  per  $m_0c^2$  by dividing by the common channel width. Finally, the EB spectra were converted into the number of photons of energy  $k$  per  $m_0c^2$  per unit photon yield. This procedure of comparing the experimental and theoretical EB spectra in terms of number of photons of energy  $k$  per  $m_0c^2$  per unit photon yield eliminates the factor due to the beta source strength and the errors associated with it. The overall uncertainty in the experimental measurements was found to be less than 10 % at 1000 keV for all cases.

#### 4. Results and discussion

The results of experimentally measured EB spectra from targets of Al, Cu, Sn and Pb for  $^{32}\text{P}$  beta particles were compared with the spectral distributions obtained from Elwert corrected (non-relativistic) Bethe-Heitler (EBH) theory, Tseng and Pratt theory and modified Elwert factor (relativistic) Bethe-Heitler theory, ( $F_{\text{mod}} \text{ BH}$ ), given by Avdonina and Pratt [5]. Figures 2 (a-d)

shows the experimental and theoretical results in terms of plots of number of photons of energy  $k$  per  $m_0c^2$  per photon yield versus photon energy  $k$ . In case of Al target, the experimental results are in agreement with the theoretical distributions obtained from EBH, Tseng and Pratt and  $F_{\text{mod}}$ BH theories, within 8 to 10 % throughout the studied energy regions. For Cu and Sn targets, the experimental results are in good agreement with Tseng and Pratt and  $F_{\text{mod}}$ BH theories. However, for Pb target the experimental results show better agreement with the  $F_{\text{mod}}$ BH theory, particularly at the high energy end. In this case, the experimental results are higher than the Tseng and Pratt theory by 11% at 800 keV, 16% at 1000 keV and 20% at 1250 keV photon energies. It is concluded that the recently modified Elwert factor Bethe-Heitler ( $F_{\text{mod}}$ BH) theory shows a better agreement with the experiment than the EBH and Tseng and Pratt theories for high  $Z$ -elements, especially at higher energy ends, while for medium  $Z$ -elements, Tseng and Pratt and  $F_{\text{mod}}$ BH theories are more accurate. However, for low  $Z$ -elements all theories are equally suitable.

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